Large-scale tidal fields on primordial density peaks ?. II Alignment of cosmic structures.

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ABSTRACT

We show that the primordial density field imposes certain degree of coherence in the orientation of density perturbations. We quantify the scale of coherence and show that is significant on scales of at least $30 - 40h^{-1}$Mpc, being more important in density fields with flat spectrum. Evidence is also presented that the reason for this coherence is that the long density waves are the dominant part of the superposition of waves which build the large-scale density peaks. As a consequence of this, small-scale peaks tend to follow the configuration of their host large-scale perturbations. Different types of alignments are investigated. It is shown that alignment of the major axes of neighbouring peaks is more prominent around the highest peaks than around the lower ones. Alignments between the major axes of peaks and the radius-vector joining their centre with the centre of a high peak were not observed. Evidence is presented that peaks develop tails extending to neighbouring peaks, as predicted by Bond (1987a, 1987b) and Bahcall (1987).

Subject headings: Galaxies: Clusters: Alignments: Gaussian Random Fields-tides

1. Introduction

Several observational works have reported different kinds and degrees of non-random orientation of cosmic structures. For example, on large-scale Gregory et al. (1981) showed that the major axis of the Perseus-Pisces supercluster coincides with the peak of the distribution of the position angle of galaxies. Djorgovski (1983) found the same effect for the Coma cluster and similar results have been reported for the Local supercluster (MacGillivray and Dood, 1985; Flin and Godlowski 1986; Kashikawa and Okamura, 1992). There also exist evidence for cluster-cluster major axes alignment over tens of megaparsecs (e.g. Binggeli, 1982; West, 1989; Plionis, 1994). On smaller-scales, a possible morphology-orientation effect has been reported by Lambas, Groth and Peebles (1989) and Muriel and Lambas (1992), who proposed that the alignment of elliptical galaxies reflects the primordial orientation of density maxima. Other point of interest concerns the evidence that first ranked galaxies, e.g cD galaxies, in linear clusters show the same orientation as their parent structures (Sastry, 1968; Carter and Metcalfe, 1980; Trevese, Cirimele and Flin, 1992).

On the theretical side there are numerical simulations which suggest that that alignment of structures arise in different cosmological models wherever filaments are formed (e.g. West, 1989; West, Dekel and Oemler, 1989; Dekel, 1989; West, Villumsen and Dekel, 1991; Plionis, Valdarnini and Jing, 1992). Moreover, there also exist increasing evidence that some coherent patterns in the orientation of density perturbations do exist in the primordial density field (Bond, 1987a, 1987b; Barnes and Efstathiou, 1987; González, 1994, 1997; Bond, Kofman and Pogosyan, 1996), discounting the action of small-scale tidal fields of neighbouring galaxies. The alignment of galaxy clusters detected up to $30 - 50$Mpc would be difficult to explain via small-scale tidal fields. Instead, Bond, Kofman and Pogosyan (1996)and González (1997, AGI97) have shown that a high degree of coherence can be produced in the density field as the result of a constructive interference of long density waves which make rare peak-patches.

This constructive interference would lead to alignment of density peaks. The degree of coherence was found to be more prominent in density fields characterized by a flat spectrum. The influence of the large-scale density field on small-scale peaks has been proposed as a possible generator of alignment of density peaks, and this in turn, to filamentary structures rehanced by the non-linear evolution of the field.

The correlation of the density field on two different filtering scales, R_a and R_b, assessed in terms of their rms (σ_a and σ_b) was already exhibited by Padmanahban (1993) and West (1994) via the parameter

$$\gamma_{ab} = \sigma_{ab}^2/(\sigma_a \sigma_b). \tag{1}$$

For a field characterized by a power law spectrum $P(k) = Ak^n$,

$$\sigma_{ab}^2 \equiv < \delta_a \delta_b > = \int P(k) W_G(kR_a) W_G(kR_b) d^3k, \tag{2}$$

where W_G is the Gaussian smoothing window function. Thus, the correlation parameter

$$\gamma_{ab}(n = 1, 0, -1, -2) = [\frac{2R_a R_b}{R_a^2 + R_b^2}]^s, \tag{3}$$

with $s = 2, 3/2, 1, 1/2$ respectively, is $\gamma_{ab} = 1$ only when the same scale of filtering is used. On the contrary, $\gamma_{ab} \to 0$ indicates that the correlation decays. A correlation is observed (Figure 2 in West, 1994) between small and large scales, being more important ($\gamma_{ab} > 0.5$) for flat spectra density fields, up to approximately $R_f = 5 - 12$. For steep spectra, the correlation is only important in the nearest neighborhood of the peaks up to $R_f < 3$. These results are similar to those found in AGI97, where the strenght of the tidal field was evaluated through the Frobenius norm. For flat spectra, long waves as well as short ones help to build the density peaks, but long waves should be the dominant part. Long density waves create a coherent effect which can persist out to large distances. If one filter the density field at a larger scale, the coherent effect dictated by the direction in which the large-scale density peak is oriented should be reflected in their internal regions. The influence of the large density waves extends

not only to the lower-scale peak in question, but also to the neighbouring peaks. Thus a correlation in the orientations of small-scale peaks is also expected. The goals of the present paper are to provide evidence that this latter statement does happen, and to propose that different kinds of alignments of cosmic structures could have a common primordial origin, as a result of the constructive interference of density modes of long wavelenght. In Sect. 2 orientations around the highest and low peaks are analized, as a function of the distance and the spectral index. We present three statistical test to prove alignment of density peaks. Radial aligment is also investigated. Sect. 3 focuses in the study of large-scale alignmemt of the type "cD-cluster", "galaxies in clusters" and "tails" connecting density peaks. In Sect. 4 we present a discussion of our results and the conclusions.

2. Alignments and its correlation scale

In this section, we address the study of a possible alignment of peaks with their neighbours, for a density field smoothed with $R_f \equiv 1 (\approx 0.66\text{Mpc})$. The orientations of all density peaks will be refered to the orientation of the highest peak in the density field. This choice is motivated because it suggests an important coherent superposition of density waves on and around the position of the highest peak. Thus, we assess the cosine of the angle subtended by the major axes of the inertia tensor of the highest peak and those of its neighbouring perturbations. In order to explore an alignment of peaks as a function of the distance, we consider all those density peaks located within shells of equal thickness $D = 10R_f \approx 7\text{Mpc}$ up to a distance of $40R_f \approx 30\text{Mpc}$. Larger distances were not considered because of the periodicity of the box at $64R_f$.

Three simple statistical tests are performed to detect and quantify any orientational anisotropy of peaks. *(a)* The mean value of $\cos\theta$ and its error in mean. Parallel and antiparallel alignments are not distinguished. For randomly oriented perturbations the distribution

of $\cos\theta$ shall uniformly be distributed between 0 and 1 with mean value 0.5. *(b)* The ratio between the number $N_{<0.5}$ of peaks with $\cos\theta < 0.5$ and the number $N_{>0.5}$ with $\cos\theta > 0.5$. An excess of $N_{>0.5}$ over $N_{<0.5}$ would indicate the existence of alignments. *(c)* We also quantify the probability P_{KS} according with the Kolmogorov-Smirnov test for the null hypothesis that the $\cos\theta$ distributions have been drawn from a uniform one.

Figure 1 shows for each of the spectral indexes, the distribution of peaks in the plane $R_f - \cos\theta$, and the histogram of the distribution in orientations of the peaks within the two first shells of radius $10R_f$. These histograms and the statistical analysis summarized in Table 1, indicate the existence of alignment effects in the initial density field. While all the models exhibit non neglegible alignments within the first shell to a distance up to $\approx 6-7$Mpc, for $n = 1, 0$ the alignment seems to persist very weakly beyond this distance. For flat spectra, the statistical significancy of the alignment extends up to at least $15 - 25$Mpc.

At the scale of clusters ($Rf \equiv 1 \approx 10$Mpc), for $n = -1, -2$, the alignment clearly extends up to at least 30Mpc. At this point, it is interesting to remark that in the N-body simulations by West, Villumsen and Dekel (1991) on the issue of cluster-cluster alignments, and Matarrese et al. (1991) who used groups of particles in a CDM model with non-Gaussian initial conditions, alignment effects were found up to a scale of $40 - 60h^{-1}$Mpc.

Before discussing the possible origin of the alignments and other consequences, we comment on three additional test which were performed in order to confirm the alignment of density perturbations.

2.1. Testing the Alignment Effect

We have identify the following three main sources of error;

1. The orientation of density peaks is defined in terms of the main axes of the deforma-

tion tensor. A straightforward test consisted in recalculating it with a higher resolution. Any considerable change of any of the elements of the inertia tensor would yield changes in the orientation of its main axes. Even when small changes in the position of the peaks in the plane $N_{pk} - \cos\theta$ were observed, the overall distribution presented no considerable changes. In any case, changes in the orientation would not produce systematic alignments.

2. The goal of the second test is to discard hide systematic errors. Two realizations were performed for each of the spectral indexes. In the first realization we identified the direction defined by the alignment of the major axes of two high peaks: the highest peak and other placed to a distance $\sim 4R_f$. This direction approximately defines the direction of alignment of the rest of the peaks, and is refered relative to the cartesian coordinates of the 64^3 grid. We repeated this for a second realization. The same scale of alignment was obtained in both realizations, however, the directions of alignment were different.

3. The third test aims to probe the 'isotropy' of the effect, i.e. the alignment has the same statistical significance when the orientations are calculated respect to another high peak, instead of using the highest one. We test both distributions against randomness in the sample using the Kolmogorov-Smirnov test for the null hypothesis that both data sets are drawn from a uniform distribution. Note that, if we choose by chance, another peak nearly aligned with the highest one, then the distribution showed in Figure 1 should only suffer little changes. Contrarily, if a peak is chosen which is not aligned, then the distribution will be clearly modified. In that case, we would be proving that alignments ocurr around high peaks. Figure 2 and Table 2 display the results for the case $n = -2$.

The results of these tests strongly suggest that the alignments are not a product of numerical artifices. If this were so, the same degree of alignment, or even absence of it, would be produced in all the models independently of the spectral index. On the contrary, there is a clear dependence on the flatness of the spectrum: flat spectra show stronger alignment effects than the steeper ones. The scale of coherence for the former of these is also larger, extending up to $15-20R_f \approx 15$Mpc. Further, the fact that the degree of alignment depends on the distance to the peak of reference it would also be difficult to explain by numerical systematics. It should also be taken into account that the influence of the large-scale density field on the deformation tensor at the position of the small-scale peaks, quantified trough the Frobenius norm in AGI97, is larger for flat spectra, $\approx 10R_f$: a scale which is reasonable consistent with the scale of alignments we have just found. The main difference between a flat and a steep spectra lies in the the superposition of the type of density waves which form the peaks. In steep spectra, like $n = 1, 0$, the superposition is dominated by short density waves. Such a superposition only locally affect the density peak; presumably the wavelength of the density waves is smaller than the separation of density maxima. In flat spectra, the long density waves are the most important. If their wavelength is larger than the mean separation of peaks, then it would lead to a coherent coupling between density perturbations.

2.2. Alignments as a function of the height of peaks

One way of exhibiting the influence of long density waves in the field and their correlation with the short waves, is through the comparison between the distribution of orientations of neighbouring peaks surrounding high peaks, with that for low ones. We restrict this analysis for $n = -2$, where a possible difference should be easily appreciated.

In Figure 3 we have plotted the distribution of orientations around the highest peak

($\nu > 3\sigma$); also shown is the distribution of orientations for low peaks ($\nu < 2\sigma$) refered to the highest one of the sample. By comparing these two distributions, we observe that low peaks surrounding low peaks, poorly follow the distribution of the highest one. Low peaks are approximately uniform distributed. Figure 3 also shows the distribution of orientations of neighbouring peaks for some of the highest peaks ($\nu > 3.8$) and around some low peaks ($\nu < 1.5\sigma$). All the neighbouring peaks within a distance of $8R_f$ from the peak of reference are considered. By comparing these figures, one first see that the influence of the highest peaks over the orientation of their neighbours is more important than the influence produced by the lower peaks. This is observed from the more marked tendency of the neighbours to cluster near $\cos\theta$. This fact, therefore, reflects the importance of long density waves. Second, the excess of short waves in $n = 1$ leads to no correlation.

We have analysed in further detail the individual characteristics of the neighbouring peaks, for each of the cases of Figure 3. The analysis included the study of the spatial distribution of the neighbouring peaks, by means of which an excess of peaks along the main axes of a high peak would be detected. The space around each peak was divided as in Figure 4. The height of the peaks and the distance of the neighbouring peaks were considered. The results can be summarized as follows; for $n = -2$ where the highest peak was $\nu \approx 4$ we analysed 30 cases. The average number of neighbours was 13.1. The number of peaks located within the two 120^o cones, at both sides of the peak, was in average 6.3, whereas within the two 60^o cones was 6.8, consistent with an isotropic distribution. An important difference is noted when one considers the number of peaks according withwhether they are higher or lower than the reference peak. Seven out of our 30 cases had two or three peaks of height approximately equal or slightly lower than the peak of reference, within the 120^o cones.

For $n = 1$, 64 high peaks were analysed. In this sample, the highest peak was $\nu \approx 2.8\sigma$

and the average number of neighbours was 16.8. Their distribution in space is also consistent with isotropy as it is reflected by the values of the average number of peaks within the region limited by the cones, 8.2, and 8.6.

2.3. Radial Alignments

In order to detect any radial alignment around the high density peaks we assess the cosine of the angle subtended by the radial vector, which joins the center of the highest peak with the center of its neighbours, and the major axis of the inertia tensor. Only the cases $n = 1$ and $n = -2$ were considered. No signals of radial alignments were detected as is suggested by the distribution of peaks in the examples of Figure 5.

The absence of radial alignments is probably not surprising, because the superposition of density waves is not isotropic as inferred from the tendency of the peaks toward triaxiality. The coherent wave bunching which forms the density peaks, make them largest along the long axis and smallest along the short axis. As the long density waves dominate the field, according to the parallel alignment earlier detected, they impose a preferential direction along which lower peaks will tend to align so that they point each other, specially if they are not very far away.

3. Large-scale Fossil Alignments

There is a possible immediate consequence of the parallel alignments observed in flat spectra: once the density field is smoothed at a larger scale is conceivable that the new large-scale peaks should preserve certain information about the 'average' triaxiality of the small-scale peaks from which they arise, especially if the two scales are not exaggerately different. Consider, for example, that the density field instead of being smoothed on a

scale R_f is smoothed on a scale $R_f + \delta R_f$. Intuitively one expect that the characteristic of the peaks such as positions, shapes and orientations are similar in both situations. In other words, the orientation of small-scale density peaks should trace the orientation of the large-scale inhomogeneities. Following this idea we analyse two possible manifestations of alignments.

3.1. A cD-cluster Alignment effect ?

A cD galaxy approximately corresponds to a Gaussian smoothing of $R_f \sim 2-3h^{-1}$Mpc. This filtering scale is not much smaller than the $8-10h^{-1}$Mpc appropriate for clusters, where smaller means that those waves of length $\sim 8h^{-1}$Mpc make a significant contribution to the rms density field on the scale of cDs. Therefore, a correlation in the orientation of the density perturbations on these scales would suggest a primordial origin for the tendency of cD galaxies to be aligned with their host cluster (Carter and Metcalfe 1981). We now address this possibility for a density field with $n = -2$.

We calculate, in a similar way to that in AGI97, the relative orientation between the density peaks of the field smoothed on scales of $2h^{-1}$Mpc and $8h^{-1}$Mpc. The major axes of the deformation tensors are once again used to ascertain the position angles. The positions of the small-scale peaks relative to the center of the large-scale fluctuation are also required. We further assume that the small-scale peaks belong to the "cluster-scale" fluctuation if they are contained within a shell of radiu $8R_f$.

Figure 6 shows one successful examples of the distributions of the orientation of the major-axes of small-scale peaks relative to the major axis of the large-scale host fluctuation. A tendency of the small-scale peaks to be aligned with the larger structure was found only in 6 out of 32 cases analysed. Though this result confirms a non negligible deviation from

random orientations, we could not obtain a small-scale peak placed in the center of the cluster-scale peaks so as to mimic a cD galaxy. The position of the small-scale peaks in general presented considerable displacements from the center of the cluster-scale peaks. In any case, it is noteworthy that the orientation of the major axes of the small-scale density perturbations follow the orientation of the large-scale peaks, similar to those involving the brightest elliptical galaxies in clusters (e.g. Sastry, 1968; Carter and Metcalfe, 1980; Rhee and Katgert, 1987).

3.2. Asymmetric tails of density peaks ?

We now briefly explore the proposal first made by Bond (1987a, 1987b) and Bahcall (1987) concerning the existence of long tails around high density peaks, which could connect them with their near neighbours. Although the detection of tails along the major axes of the peaks is hard to perform for the whole field, mainly due to the different threshold values of the density contrast to explore, we provide some supporting evidence of their existence.

In the detection of peaks tails we proceed by interpolating the density at points surrounding the peaks and then plotting isodensity surfaces around them, looking at their shape and length along their major axes. Isodensity contours around neighbouring peaks will be trivially connected if a low density threshold is chosen. We are interested in detecting 'bridges' between peaks when a high density threshold ($\nu < 15\%\nu_{peak}$) is considered. This means, isodensity contours extended along the main axes of high peaks.

Figure 7 shows an example of the positive results in searching for tails, for $n = -2$. 20 peaks were analysed in this way but only those (3 cases) peaks with a near (separated a distance $< 10R_f$) neighbour of similar height presented tails. This result further support the idea that density modes produce a coherent orientation along the major axes of high peaks

when their wavelengths are larger than the mean separation of peaks, which in the case $n = -2$ is $5R_f$ for peaks of arbitrary height, and $\approx 8R_f$ for peaks with $\nu > 2.5$ (González, 1994). We can argue for these peaks that, as the density field evolves, the small-scale peaks are carried along with the large-scale distribution of mass, which should reinforce their initial parallel alignment.

4. Discussion and Conclusions

We have found evidence of parallel alignment of density perturbations on different scales. We found for example that the small-scale density peaks follow a similar orientation to that of the cluster-scale major axis. This effect is more important for flat spectra. When filtering on cluster-scales is considered, the alignments extend up to $\approx 30h^{-1}$Mpc, in agreement with the observational evidence of cluster-cluster alignments (.e.g. Plionis 1994). Further, the scale of correlation deduced from the analysis of changes in the deformation tensor, in AGI97, and the scale of alignments reasonably agree with the theoretical scale of correlations. Similar agreement is found with the strength of the tidal influence on the peaks, estimated through the Frobenius norm.

Evidence was given that flat spectra constitute a coherent density field: i.e. the orientation of small-scale peaks follow the orientation of the large-scale fluctuations. Whereas the correlations of the density field smoothed at two different scales are a natural consequence of Gaussian density fields, the alignments are related to the flatness of the spectrum. This is clearly indicated by the absence of alignments on large scales for steep spectra.

Based on these results we conclude that an important degree of large-scale alignment of the cosmic structure is of primordial origin, in agreement with Bond, Kofman and Pogosyan (1996). Some numerical simulations (e.g. Melott and Shandarin 1989; Kofman et al. 1992)

have shown that the development of filamentary structures is a generic feature of density fields with flat spectra. Our results, which have proved to be quite sensitive to the type of spectrum of the density field, indicate therefore than alignments and filamentary structures are two correlated aspects. Bond (1987a, 1987b) and Bahcall (1987)have visualized the filamentary structure of the Universe as primordial density peaks with long tails connecting peaks. These bridges would be dynamically enhanced by the non-linear evolution of the field. This idea can account not only for the filamentary structure but also for the alignment of structure. We have provided evidence of the existence of such long tails in flat spectra and coherence in the orientations of peaks. As another possible consequence of these tails, which deserve more attention, is the anisotropic shape of the cluster-galaxy correlation function (Bahcall 1987). Both the spatial cluster-cluster correlation function and the cluster-cluster alignment joined by bridges can give a natural explanation for such anisotropy.

There are two important factors which will determine the final orientation of collapsed objects which form at the sites of density peaks; a) the tidal stress, which is produced by the surrounding distribution of mass, b) and the initial orientation of the density perturbation relative to the tidal field. The main effect of the tidal shear is to change the orientation of the deformation tensor, which leads to significantly modify their initial orientation and shape (e.g. van de Weygaert and Babul, 1994). Tidal stress is stronger for the cases $n = -1, -2$.

As the density field enters non-liner regime, different Fourier modes get couple, giving an extra dynamical contribution to their initial statistical correlation both spatial and orientational. The initial orientational anisotropy is further rehanced by the intrinsic triaxiality of peaks which follow the Zel'dovich predictions. If the peaks possess long tails connect them with near neighbours, then the simultaneous collapse with the large-scale density perturbations would reinforce the anisotropy of the initial chained peaks. The signals of alignments found for flat spectra reflect the important contribution of large-scale fluctuations, which

both induce strong tidal fields and make the collapse of cluster to follow each other in quicker succession. From this point on, it is necessary to perform numerical simulations in order to elucidate whether the non-linear coupling of density waves is not enough so as to erase some of their initial coherent superposition.

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Fig. 1.— Distribution of peaks respect to the highest peak in the sample, as a function of their relative orientation and their separation. The histogram shows the distribution of peaks with separations $< 15R_f$. A significant alignment effect is observed up to $\approx 20R_f$ for $n = -1, -2$.

Fig. 2.— A comparison of the orientation distribution of neighbouring peaks, calculated from any of the highest peaks.

Fig. 3.— *(a)* The distribution of orientations of high peaks $\nu > 3.8\sigma$ –relative to the highest one– in a model with $n = -2$. *(b)* The distribution of low peaks $\nu < 1.5\sigma$. Also shown are the orientations of neighbouring peaks for some of the highest and low peaks.

Fig. 4.— The space around the highest peak is divided in two areas as illustrated here.

Fig. 5.— No radial alignments are detected; the orientation of the major axes of peaks relative to the radius vector joining their centre with the centre of the nearest high peaks.

Fig. 6.— *cD-cluster* alignments.

Fig. 7.— One case in which a long tail connect high density peaks.

Table 1. Statistics for Alignments

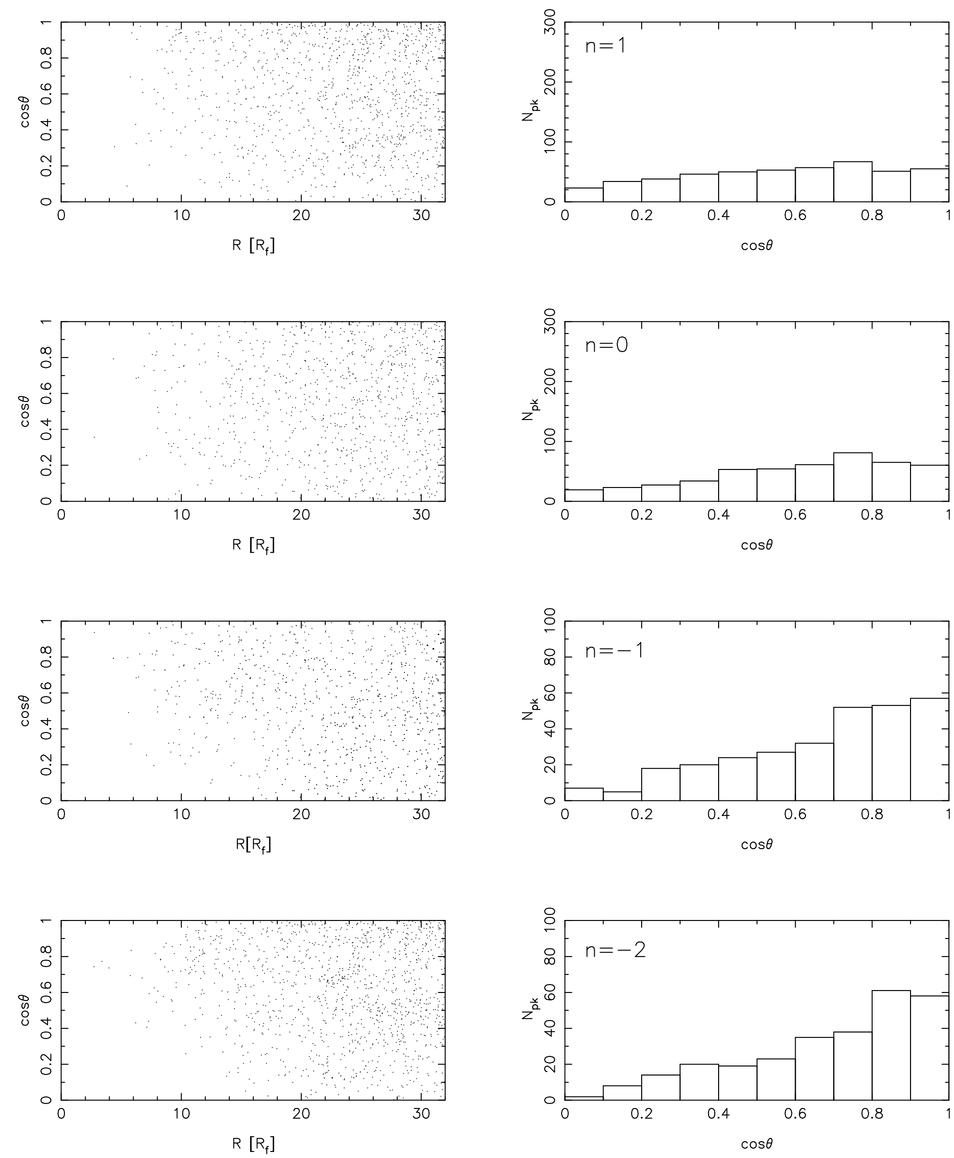
Spectral index n $D(h^{-1})$Mpc	$< \cos\theta >$	$N_{<0.5}/N_{>0.5}$	P_{KS}
$n = 1$			
$0 \leq D \leq 10$	0.572 ± 0.0219	198/288	$< 10^{-16}$
$10 \leq D \leq 20$	0.539 ± 0.0012	1052/1212	0.05
$20 \leq D \leq 30$	0.492 ± 0.0312	1274/1348	0.27
$30 \leq D \leq 40$	0.485 ± 0.0241	316/323	0.46
$n = 0$			
$0 \leq D \leq 10$	0.615 ± 0.0219	143/278	$< 10^{-16}$
$10 \leq D \leq 20$	0.579 ± 0.0012	952/1132	$< 10^{-3}$
$20 \leq D \leq 30$	0.522 ± 0.0312	1035/1114	0.13
$30 \leq D \leq 40$	0.505 ± 0.0241	153/168	0.23
$n = -1$			
$0 \leq D \leq 10$	0.684 ± 0.0310	94/196	$< 10^{-17}$
$10 \leq D \leq 20$	0.651 ± 0.0112	486/812	$< 10^{-8}$
$20 \leq D \leq 30$	0.626 ± 0.0731	919/1158	$< 10^{-9}$
$30 \leq D \leq 40$	0.582 ± 0.0324	385/469	0.02
$n = -2$			
$0 \leq D \leq 10$	0.737 ± 0.0119	63/214	$< 10^{-19}$
$10 \leq D \leq 20$	0.715 ± 0.012	262/750	$< 10^{-9}$
$20 \leq D \leq 30$	0.709 ± 0.003	422/1167	$< 10^{-5}$
$30 \leq D \leq 40$	0.702 ± 0.0241	114/325	$< 10^{-7}$

Note. — Different statistical test to quantify the alignment effects around the highest density peaks for power law spectra.

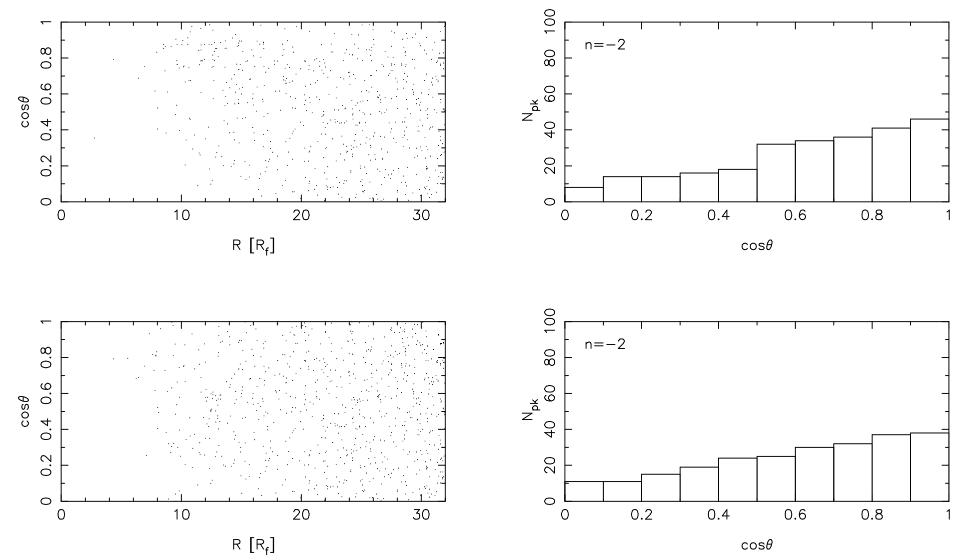
Table 2. Alignments

Spectral index n $D(h^{-1})$Mpc	$< \cos\theta >$	$N_{<0.5}/N_{>0.5}$	P_{KS}
$n = -2$			
$0 \leq D \leq 10$	0.724 ± 0.0149	80/194	0.22
	0.717 ± 0.0169	68/206	
$10 \leq D \leq 20$	0.705 ± 0.0253	293/757	0.31
	0.715 ± 0.0162	318/732	
$20 \leq D \leq 30$	0.695 ± 0.0342	493/1096	0.37
	0.702 ± 0.0142	467/1122	
$30 \leq D \leq 40$	0.687 ± 0.0141	105/334	0.28
	0.694 ± 0.0235	128/311	

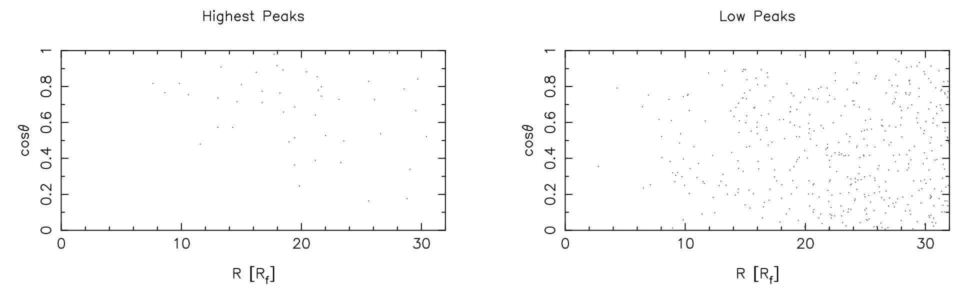
Note. — Statistical test to show the equivalence of the alignments calculated from different peaks, in a model with $n = -2$.

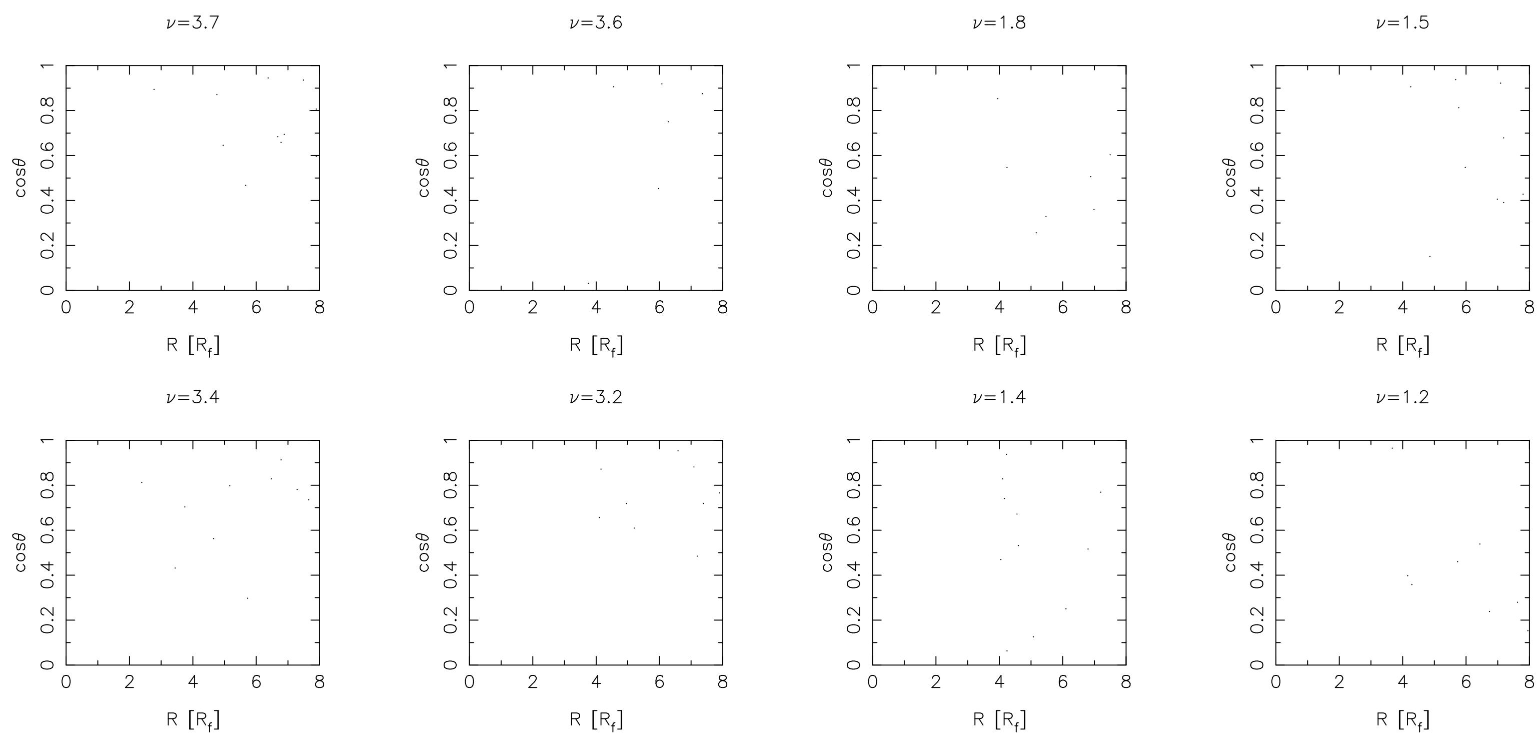


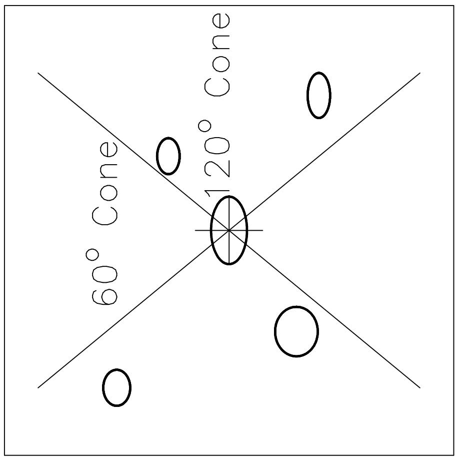
n=1
n=0
n=−1
n=−2
cosθ
R [R_f]
N_pk

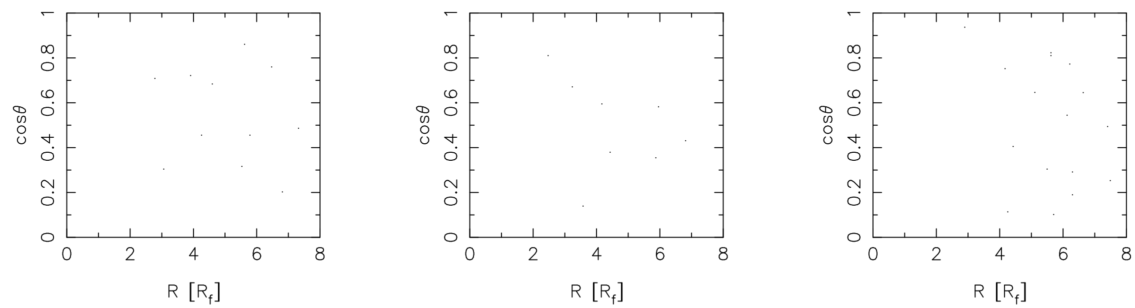


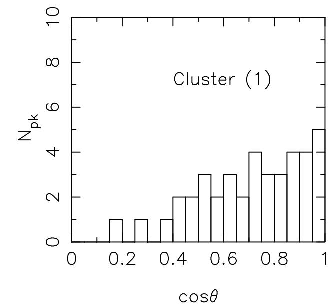
cosθ
R [R_f]
N_pk
n=−2
cosθ
cosθ
R [R_f]
N_pk
n=−2
cosθ

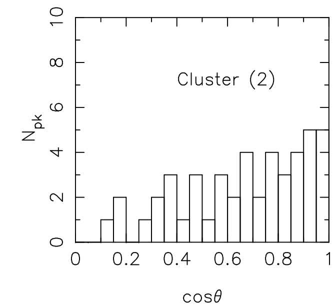

Highest Peaks
Low Peaks
cosθ
R [R_f]
0
0.2
0.4
0.6
0.8
1
0
10
20
30

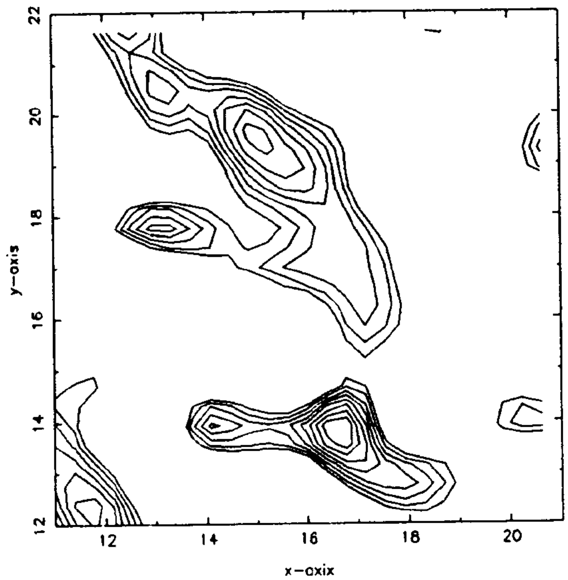

ν=3.7
ν=3.6
ν=1.8
ν=1.5
ν=3.4
ν=3.2
ν=1.4
ν=1.2
cosθ
R [R_f]


120° Cone
60° Cone


cosθ
R [R_f]
cosθ
R [R_f]
cosθ
R [R_f]


Cluster (1)
N_{pk}
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
$\cos\theta$


Cluster (2)
N_{pk}
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
$\cos\theta$



y-axis
x-axix
12
14
16
18
20
22